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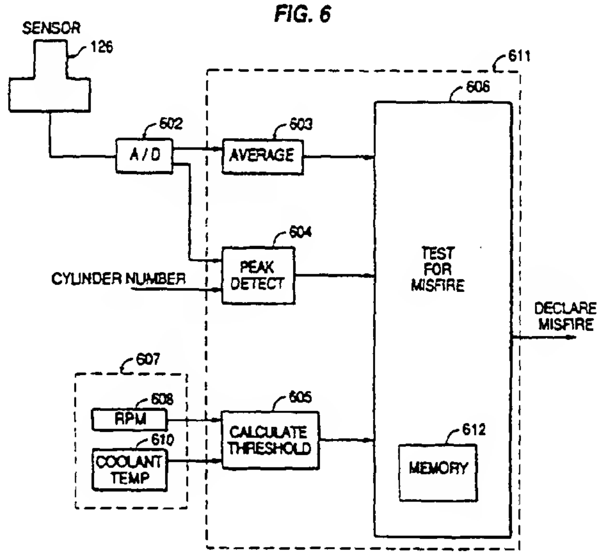
(54) **Detecting engine cylinder misfire**

(57) Exhaust manifold pressure measured by a single gauge-type pressure sensor 126 positioned in the exhaust manifold of an internal combustion engine is used to detect misfires in any cylinder of the engine. The pressure sensor detects the exhaust manifold pressure and feeds a signal to a microcomputer 611 via an analog-to-digital converter 602. A data processing device 606 monitors the pressure waveform created by the data from the sensor 126 to determine if a misfire occurs. Partial or complete misfiring in a cylinder reduces the strength of the pressure pulse for that cylinder, allowing the data processing device to identify the misfire. The data processing device may determine a misfire by comparing the peak sensed pressure for a cylinder with a minimum pressure value derived from the running average peak pressure for all cylinders over a combustion cycle, less a pressure threshold reduction as a function of engine speed and fuel consumption rate. The arrangement may be used in a fuel control system in which the air/fuel ratio is made leaner until misfiring just fails to occur.

FIG. 6



At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

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FIG. 1

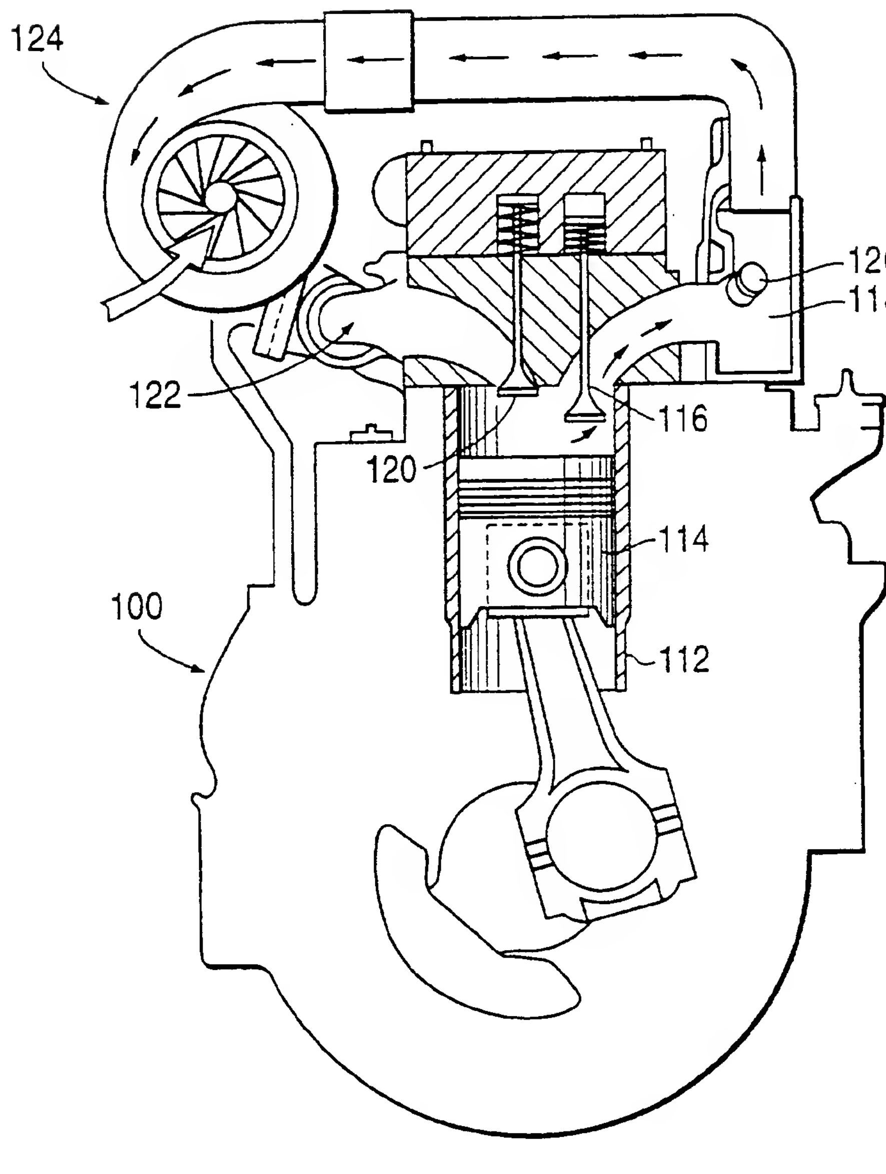


FIG. 2A

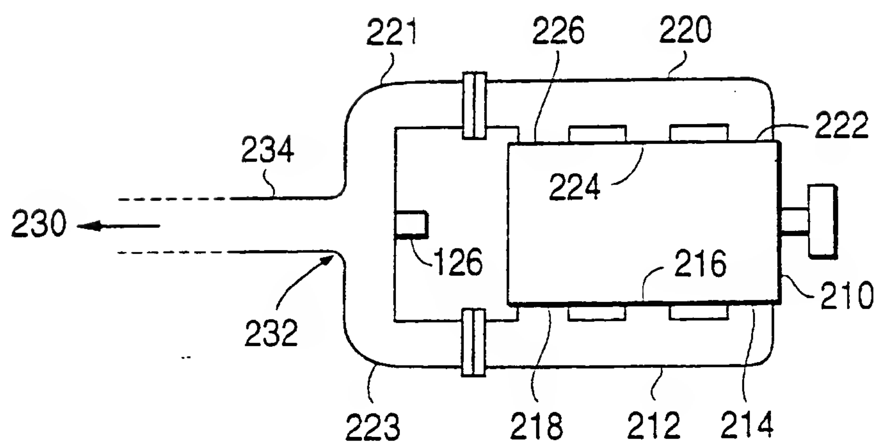

221
226
220
222
234
224
230
126
216
210
232
223
218
212
214

FIG. 2B

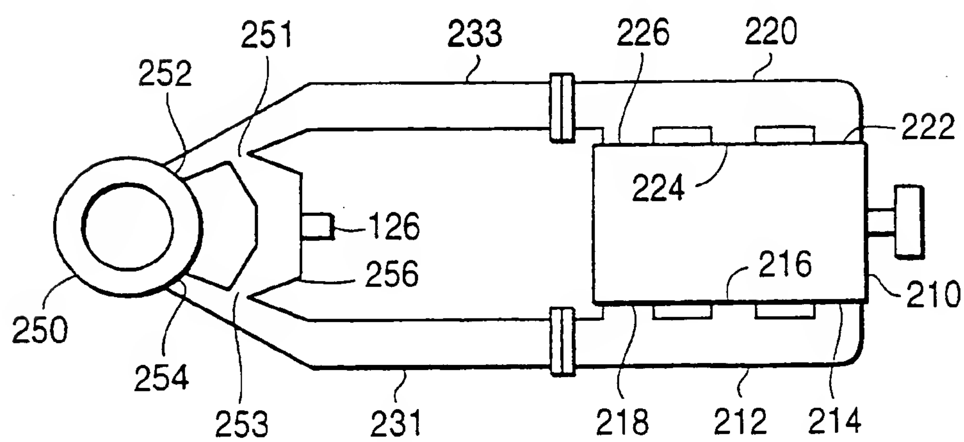

251
233
226
220
252
222
224
126
256
216
210
250
254
253
231
218
212
214

FIG. 3

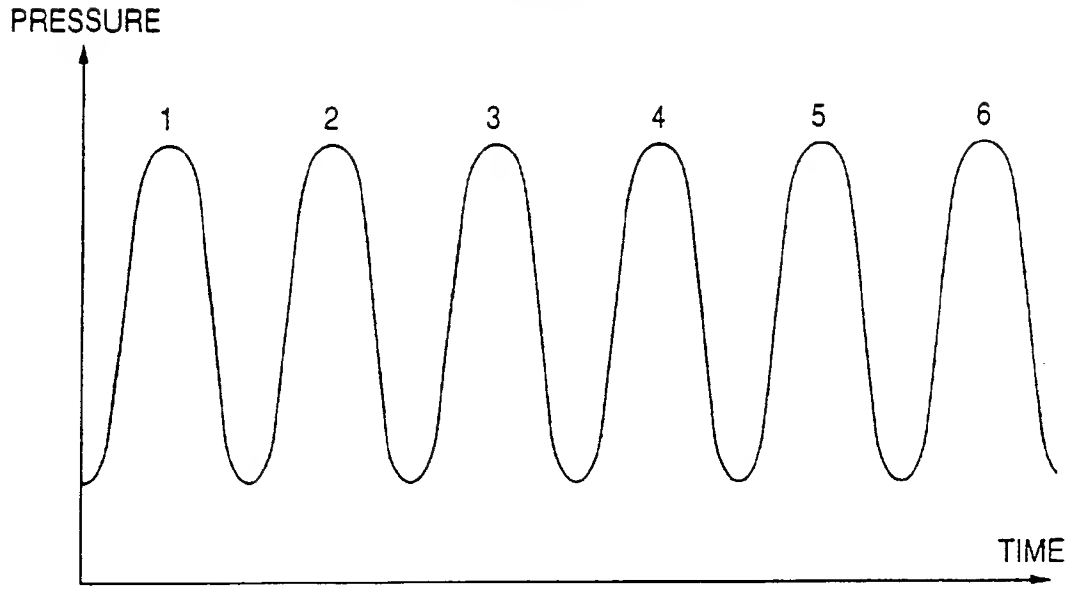


FIG. 4

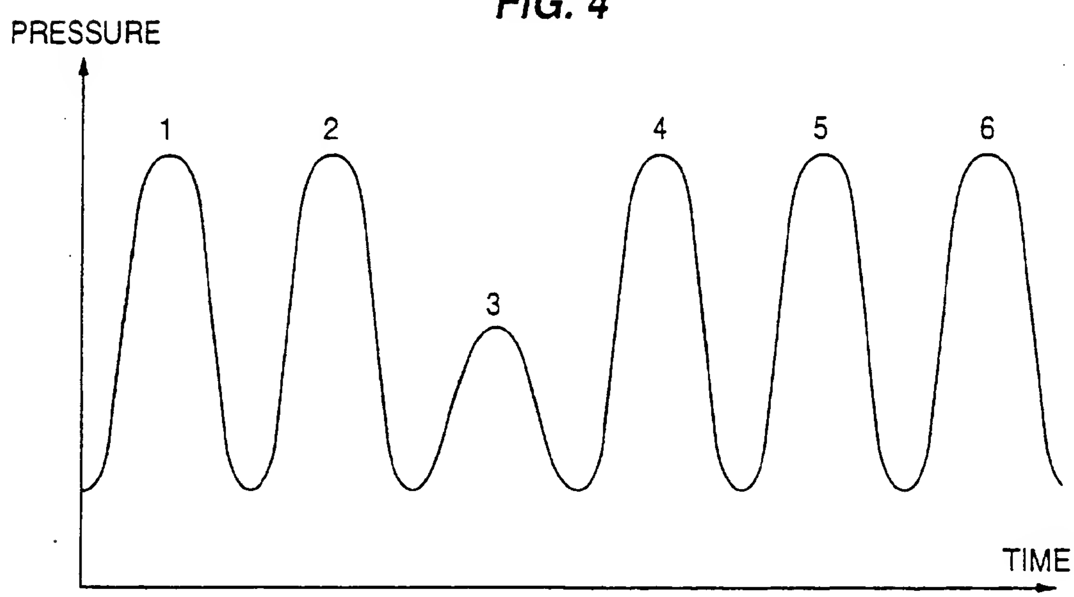
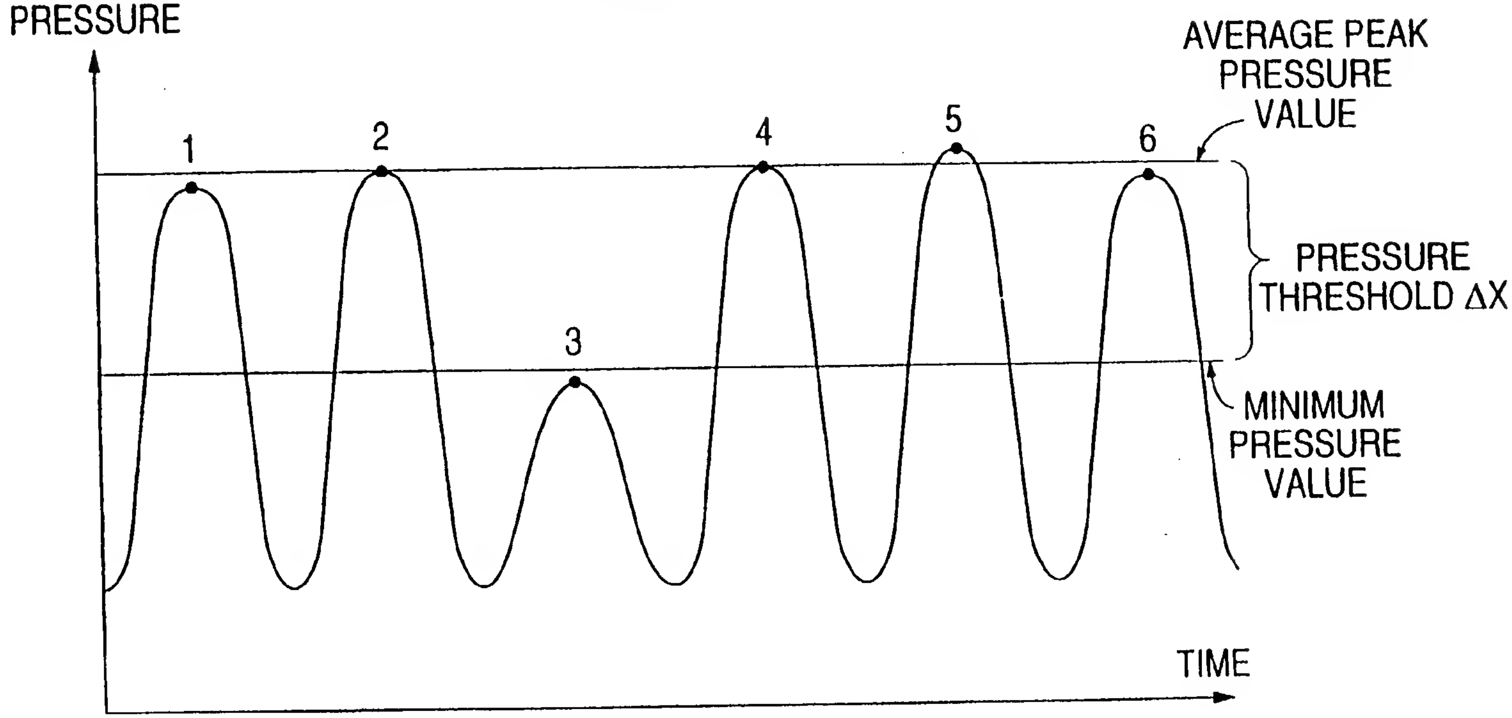


FIG. 5


PRESSURE
AVERAGE PEAK PRESSURE VALUE
1
2
3
4
5
6
PRESSURE THRESHOLD ΔX
MINIMUM PRESSURE VALUE
TIME

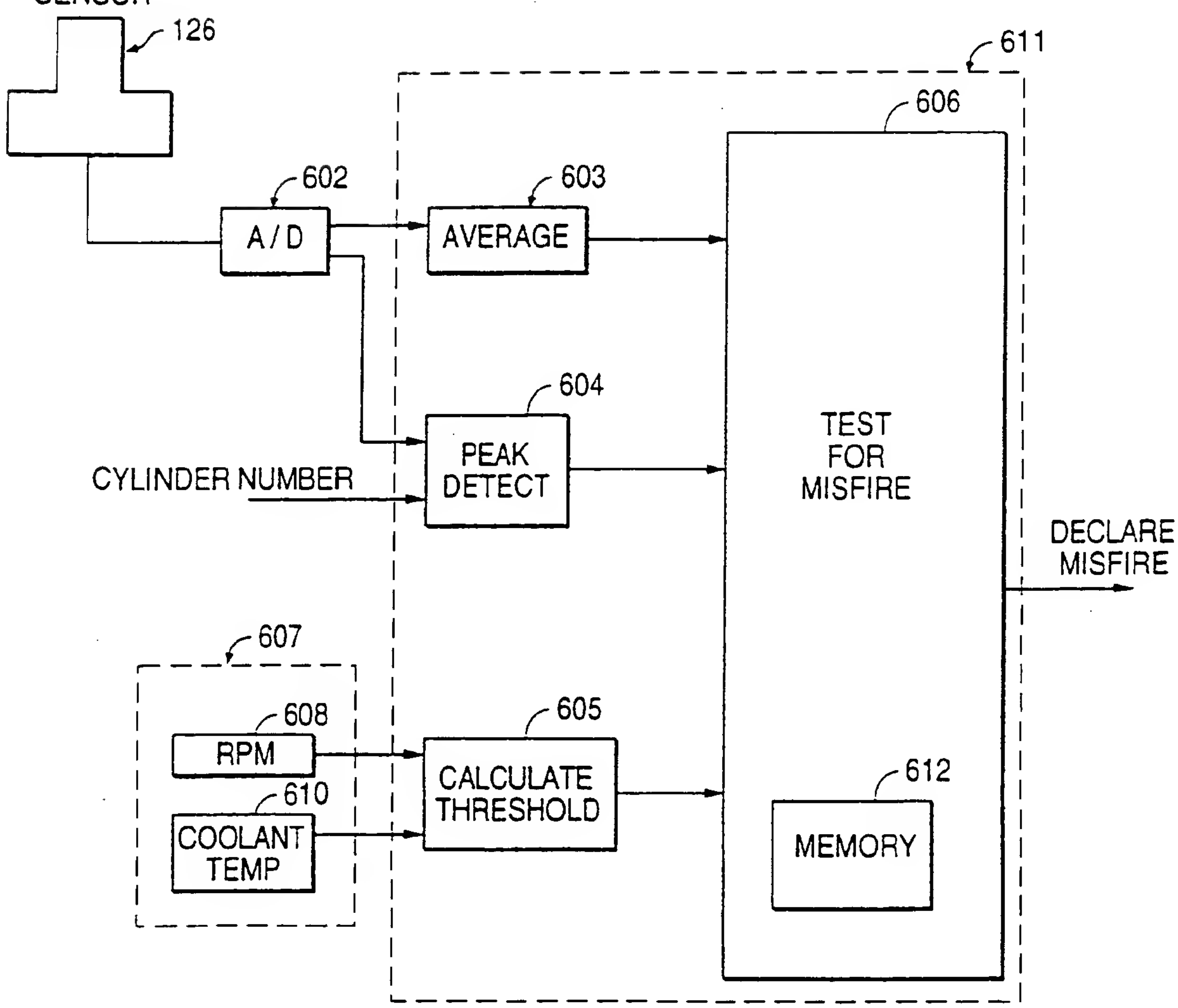

SENSOR
126
611
606
602
603
A / D
AVERAGE
604
PEAK DETECT
TEST FOR MISFIRE
CYLINDER NUMBER
DECLARE MISFIRE
607
605
608
RPM
610
COOLANT TEMP
CALCULATE THRESHOLD
612
MEMORY

FIG. 6

6/7

FIG. 7

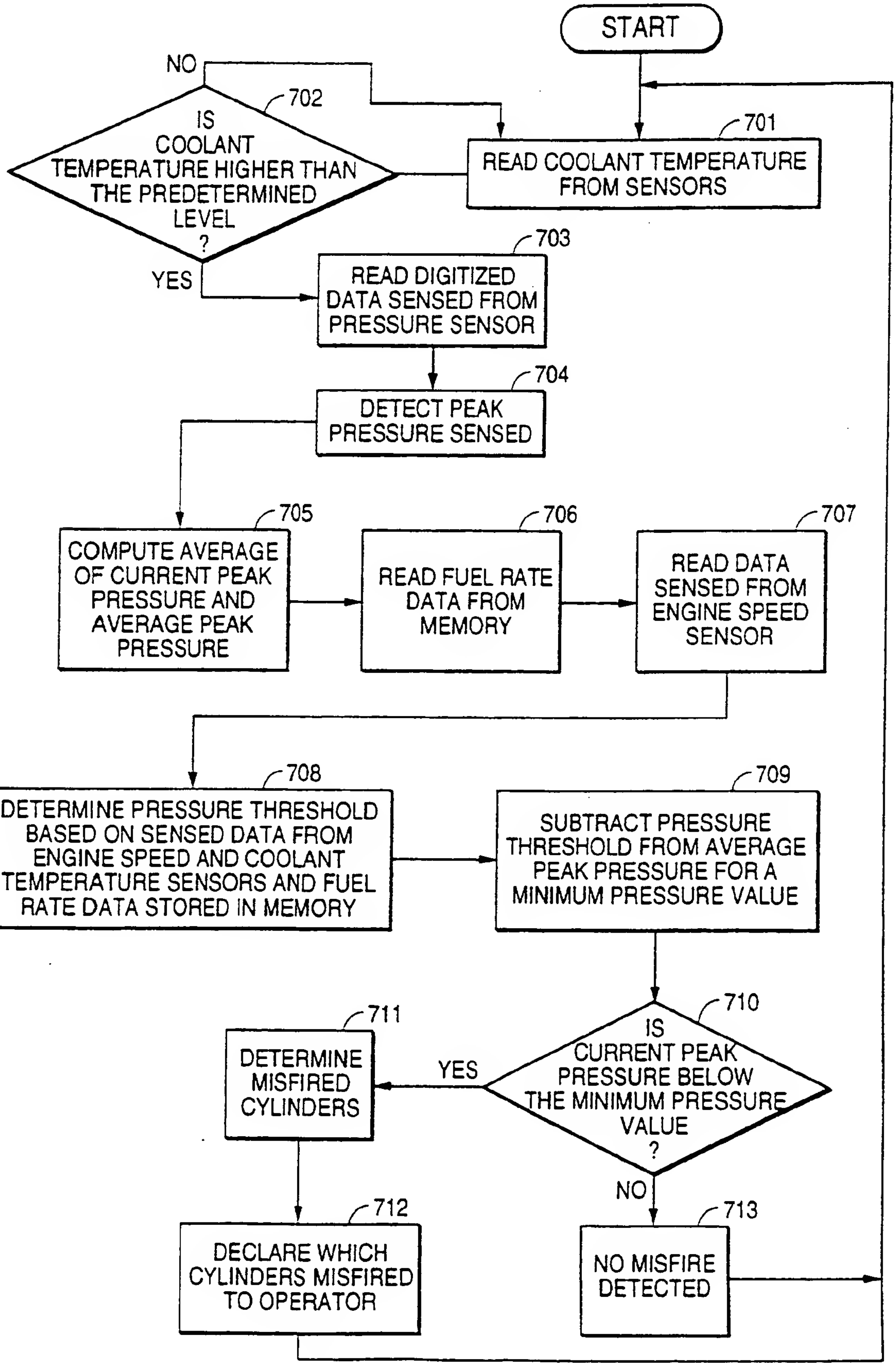
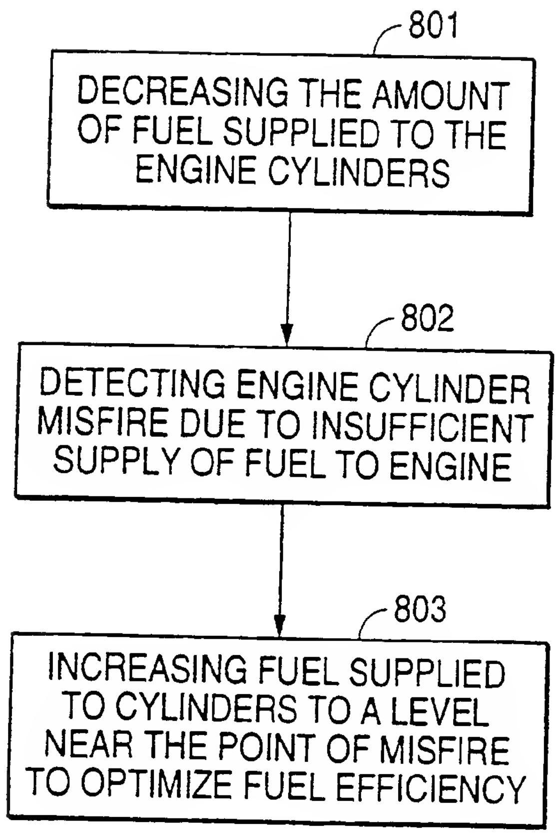

START
701
READ COOLANT TEMPERATURE FROM SENSORS
702
IS COOLANT TEMPERATURE HIGHER THAN THE PREDETERMINED LEVEL ?
NO
YES
703
READ DIGITIZED DATA SENSED FROM PRESSURE SENSOR
704
DETECT PEAK PRESSURE SENSED
705
COMPUTE AVERAGE OF CURRENT PEAK PRESSURE AND AVERAGE PEAK PRESSURE
706
READ FUEL RATE DATA FROM MEMORY
707
READ DATA SENSED FROM ENGINE SPEED SENSOR
708
DETERMINE PRESSURE THRESHOLD BASED ON SENSED DATA FROM ENGINE SPEED AND COOLANT TEMPERATURE SENSORS AND FUEL RATE DATA STORED IN MEMORY
709
SUBTRACT PRESSURE THRESHOLD FROM AVERAGE PEAK PRESSURE FOR A MINIMUM PRESSURE VALUE
710
IS CURRENT PEAK PRESSURE BELOW THE MINIMUM PRESSURE VALUE ?
YES
NO
711
DETERMINE MISFIRED CYLINDERS
712
DECLARE WHICH CYLINDERS MISFIRED TO OPERATOR
713
NO MISFIRE DETECTED

FIG. 8


801
DECREASING THE AMOUNT OF FUEL SUPPLIED TO THE ENGINE CYLINDERS
802
DETECTING ENGINE CYLINDER MISFIRE DUE TO INSUFFICIENT SUPPLY OF FUEL TO ENGINE
803
INCREASING FUEL SUPPLIED TO CYLINDERS TO A LEVEL NEAR THE POINT OF MISFIRE TO OPTIMIZE FUEL EFFICIENCY

2301898

"A SYSTEM AND METHOD FOR DETECTING ENGINE CYLINDER MISFIRE "

TECHNICAL FIELD

This invention is generally directed to the field of internal combustion engines and more particularly to a system and method for detecting engine cylinder misfires in such internal combustion engines.

BACKGROUND

In order to meet the demand for increased internal combustion engine efficiency and improved emissions control, engine manufacturers have developed techniques for constantly monitoring the operational characteristics of the engine to determine when engine operation is abnormal or outside of prescribed tolerances. This is particularly true with advanced engines which are designed to meet or exceed state-of-the art fuel economy and emissions control. Even more importantly, an internal combustion engine can be damaged, requiring costly repairs or earlier than normal overhaul, if it is operated in a non-optimal or malfunctioning condition.

One such characteristic of engine operation is that of an engine cylinder misfire. An engine cylinder misfire can occur due to failed ignition of the fuel-air mixture within an engine cylinder (lack of combustion) or the incomplete ignition of the fuel-air mixture caused by too lean of a mixture (incomplete combustion). Each of these misfires affect engine performance and can result in increased emissions and reduced fuel economy.

Damage to a vehicle can occur if an engine misfire condition is not detected and corrected. For example, many internal combustion engine driven

vehicles employ catalytic converters to reduce the amount of pollution generated by the vehicle exhaust. Due to the structure and operation of catalytic converters, a large amount of heat is usually present within the converter itself. Therefore, where there is a lack of combustion or incomplete combustion, fuel is passed through the exhaust to the catalytic converter where, as a result of the heat in the converter, it combusts. The additional heat generated from this direct combustion in the catalytic converter quickly destroys the converter.

Various approaches have been employed in the prior art to detect engine misfires. One technique used by the prior art to detect engine cylinder misfire is to position a pressure transducer within the exhaust path of an internal combustion engine. Generally, the pressure transducer converts exhaust gas pressure to an electrical signal that can be processed to detect engine cylinder misfire, but none of the prior art methods take into account a multitude of present operating conditions of an internal combustion engine including fuel rate, engine speed, and coolant temperature, in combination with the output of the pressure transducer to detect an engine misfire.

For example, U.S. Patent No. 5,193,513 to Marko et al. discloses a misfire detection system for use in an internal combustion engine in which an exhaust pressure sensor, a position sensor for sensing the rotational position of the engine, and an analog-to-digital converter for digitizing an analog signal received from the pressure sensor are employed. The digitized pressure data is compared using a data classifier (i.e. pattern recognition system) that is trained to recognize data signatures of individually misfiring cylinders. To

train the classifier, the engine is operated in a service bay and engine data is collected during both intentionally induced misfires and under normal conditions. This data is then presented to the data classifier in a training operation. Engine misfire detection systems such as the one disclosed in Marko, et al., however, fail to compare a multitude of engine operation characteristics to sensed engine cylinder peak pressures to detect partial or complete engine misfires.

Using sampled engine operation data retrieved from sensors located within or on the internal combustion engine to detect engine speed, coolant temperature and fuel rate, for example, would allow a user to monitor and detect possible engine misfires in real-time during the operation of the vehicle. This would be accomplished by comparing the engine operation characteristics with the sensed cylinder exhaust pressure for each combustion cycle of an internal combustion engine. The prior art provides a variety of methods for detecting engine cylinder misfire for a combustion cycle, however, fails to rely on engine operation characteristics in calculating partial or complete engine cylinder misfires. For example, U.S. Patent 3,965,677 to Goto et al. discloses a misfire detecting apparatus in which the suction pressure of an engine is detected and used to calculate a threshold level wherein a cylinder misfire is declared if the exhaust gas pressure exceeds this threshold level. Furthermore, U.S. Patent 3,983,754 to Deguchi et al. discloses an apparatus for detecting misfires in a multi-cylinder internal combustion engine in which pressure responsive devices are provided in the branches of the exhaust manifold or exhaust ports and the outputs of these devices are compared to

detect an engine cylinder misfire. U.S. Patent 4,567,755 to Ootsuka et al. discloses an ignition/misfire detector for an internal combustion engine in which a pressure detection unit is used to detect changes in combustion pressure in the engine and an ignition/misfire detection unit is used to determine the occurrence of an engine ignition misfire. Finally, U.S. Patent 3,924,457 to Ōshima et al. discloses a misfire detecting device for an internal combustion engine in which an exhaust gas introducing tube is provided adjacent to an exhaust port in an exhaust passage to provide exhaust gas to a pressure transducer disposed at one end of the exhaust gas introducing tube to determine pressure fluctuation which may indicate a possible engine cylinder misfire. All of these methods of detecting engine cylinder misfire fail to employ a multitude of present engine operating conditions to provide an efficient engine cylinder misfire detection system.

A novel engine cylinder misfire detection system and improvement over the prior art is disclosed in U.S. Application Serial No. 08/084,071, filed on June 30, 1993, and is assigned to Cummins Engine Company, the same assignee of the present invention. This application discloses an engine cylinder misfire system that uses a sensor to monitor an engine cylinder for all engine cycles and to provide an average of the detected output for each cylinder. Furthermore, the engine speed and fuel rate of the internal combustion engine are used to provide a more effective engine cylinder misfire detection system. Nevertheless, the invention disclosed in U.S. Application Serial No. 08/084,071 is directed to a system for detecting low

power in at least one cylinder of a multi-cylinder engine. Furthermore, this application discloses the use of multiple pressure sensors, specifically one sensor for each cylinder to provide engine misfire detection.

Upon sensing a multitude of engine operation characteristics in real time, including engine exhaust pressure, a suitable algorithm must be formulated to process the electrical signals generated by the sensors into a readable form and to perform a series of operations to determine a partial or complete misfire. For example, in computing when an engine cylinder misfire has occurred, the prior art suggests a method in which a peak value and an average value is used for a sensed condition to detect the malfunction of an engine cylinder. For example, U.S. Patent No. 5,144,929 to Hosoya et al. discloses an apparatus which calculates a peak level of a sensed condition and an average level of the sensed condition and uses those values to generate a peak threshold level using a peak threshold calculator. The average level is amplified using the peak threshold calculator and an offset value is added to this value to provide the peak threshold level. A subtractor is then used for making a comparison between the peak level and the peak threshold to provide a derivation level which is used to determine whether a malfunction has occurred in the engine cylinder. Although Hosoya et al. appears to disclose a method for utilizing sensed operating data to determine whether a malfunction in an engine cylinder has occurred, it fails to provide an algorithm that processes engine operating characteristics such as fuel rate, coolant temperature and engine speed in combination with a sensed engine exhaust

pressure to provide a reliable engine cylinder misfire detection system and method.

Therefore, the inventor has recognized a need for an engine cylinder misfire detection system that samples engine operating characteristics in real time and utilizes these characteristics in combination with a sensed engine cylinder pressure value for each combustion cycle of an internal combustion engine to determine whether an engine cylinder is operating inappropriately. A reliable engine cylinder misfire detection system that provides this function is necessary to increase engine performance, decrease engine emissions and improve fuel economy.

SUMMARY OF THE INVENTION

It is an object of the invention to provide an improved system and method for determining when an engine cylinder misfire occurs in an internal combustion engine.

It is a still further object of the present invention to provide a system and method for accurately and reliably detecting an engine cylinder misfire by analyzing exhaust manifold pressure to determine when an engine cylinder misfires occurs.

It is a still further object of the present invention to provide a system and method for accurately and reliably detecting either a complete lack of combustion or a partial combustion within an engine cylinder.

It is another object of the present invention to provide a system and method which calculates the average peak pressure for a combustion cycle to determine whether a possible misfire has occurred.

It is yet another object of the present invention to provide a system for determining an internal combustion engine cylinder misfire that operates using a single pressure sensor for any number of engine cylinders.

It is a still further object of the present invention to provide a system and method for detecting internal combustion engine misfire in which a single sensor is employed to detect engine misfires in an engine having multiple exhaust manifolds.

It is further an object of the present invention to provide a system and method for detecting engine cylinder misfire by comparing a current peak pressure for an engine combustion cycle with a running average peak pressure sensed from previous engine combustion cycles.

It is also an object of the present invention to provide a system and method for accurately detecting engine cylinder misfire using a wide range of engine operation parameters to calculate a pressure threshold for use in determining individual cylinder misfires.

It is yet another object of the present invention to calculate a pressure threshold based on at least one or more of sensed engine speed, fuel rate, and coolant temperature wherein sensed current peak exhaust pressure is compared to the average peak pressure minus the pressure threshold to detect an engine cylinder misfire.

These and other objects are achieved by a system and method in which the exhaust manifold pressure is measured by a single pressure sensor to detect misfires in all cylinders of an internal combustion engine. Specifically, a pressure sensor, such as a piezoelectric sensor or other gauge type sensor, is mounted in the exhaust manifold upstream of the turbocharger to monitor the exhaust manifold pressure relative to the ambient atmospheric pressure. During a normal combustion cycle, when the exhaust valve opens, the in-cylinder pressure is significantly higher than the exhaust manifold pressure causing pressure pulses in the exhaust manifold corresponding to each exhaust value opening. A normal combustion cycle is a period in which all engine cylinders have fired or have attempted to fire one time. After sampling the peak pressure pulses created by each exhaust valve opening, the pressure sensor signal is digitized by an analog-to-digital converter and sent to a processor to be analyzed and stored in memory.

When a combustion cycle is completed, the running average peak pressure for all of the engine cylinders is calculated. The running average peak pressure is determined by averaging the current peak pressure value (for a single cylinder) with the previous average of peak pressure values (for two or more cylinders) sensed during the combustion cycle. If a cylinder suffers from a partial or complete misfire, the strength of the pressure pulse for that cylinder will be reduced. To actually detect engine misfire, the processor calculates a pressure threshold as a function of at least one of the engine speed and fuel consumption rate. The pressure threshold is calculated as a percentage or an absolute pressure which is subtracted from the running

average peak pressure to determine a minimum pressure value. If the exhaust manifold pressure for any cylinder is below the minimum pressure value, a misfire is declared.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 depicts a pressure sensor located in an exhaust manifold of an internal combustion engine which embodies the present invention;

Fig. 2a illustrates an embodiment of the present invention in which the pressure sensor is located in an exhaust gas system downstream from the exhaust manifold;

Fig. 2b illustrates another embodiment of the present invention in which the pressure sensor is located in a twin-entry turbo exhaust gas system downstream from the exhaust manifold;

Fig. 3 illustrates the output from the pressure sensor in a normally operating internal combustion engine;

Fig. 4 illustrates the output from the pressure sensor when one cylinder of the internal combustion engines misfires;

Fig. 5 illustrates a threshold and average peak pressure value used to detect an engine misfire in carrying out the present invention;

Fig. 6 is a block diagram of a system that can be used to detect an internal combustion engine misfire in carrying out the present invention;

Fig. 7 is a flowchart of a software algorithm used to determine the occurrence of a misfire based on the calculated running average peak pressure and pressure threshold in carrying out the present invention; and

Fig. 8 illustrates a process of obtaining optimal fuel efficiency using the system and method of determining engine cylinder misfire of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Fig. 1 illustrates a preferred embodiment of the present invention. In particular, the preferred embodiment includes a pressure sensor 126 located in an exhaust manifold 118 of an internal combustion engine. Internal combustion engine 100 comprises a cylinder 112, a piston member 114, an exhaust valve 116, an exhaust manifold 118, an intake valve 120, an intake port 122, a turbocharger 124, and the pressure sensor 126. In the preferred embodiment, internal combustion engine 100 will operate in a natural gas environment. The internal combustion engine 100, however, may also operate using diesel or gasoline fuel. Moreover, the present invention may be developed to meet the requirements of CARB OBD II set by the California Regulations Board.

The present invention, in accordance with the preferred embodiment will operate in a natural gas environment to provide enhanced fuel efficiency. In a natural gas environment, the spark-ignited engine will operate at a steady state speed while the fuel is slowly leaned out until an engine misfire occurs. After the misfire occurs, the fuel is then minimally increased to a level near the misfiring point to enable the engine to run as lean as possible. By operating the natural gas engine near the misfire point, the fuel economy is greatly improved.

Pressure sensor 126 is mounted in exhaust manifold 118 to monitor the exhaust manifold pressure relative to the ambient atmospheric pressure. Pressure sensor 126 is preferably a gauge type sensor, such as a piezoelectric sensor or a capacitive ceramic sensor, which is able to withstand the extreme temperatures of the gases in exhaust manifold 118. One skilled in the art, however, will appreciate that any sensor with the above characteristics may be used.

During a combustion cycle, when the exhaust valve 116 opens, the in-cylinder pressure is significantly higher than the exhaust manifold pressure. A combustion cycle is a period during which all engine cylinders have fired or have attempted to fire one time. Consequently, a pressure pulse is created within the exhaust manifold for each combustion cycle of the engine. As the exhaust gases are released from each cylinder, they are routed downstream toward the turbocharger 124. Pressure sensor 126 is preferably located upstream from the turbocharger at the end of exhaust manifold 118, as shown in Fig. 1.

Due to this location, the single pressure sensor 126 can be used to provide pressure data for each cylinder of the engine. The engine cylinders fire sequentially during a combustion cycle causing exhaust gases to be released at different time intervals. As each cylinder releases exhaust gases, the pressure sensor 126 monitors and samples the pressure pulse created in the exhaust manifold. Subsequently, the pressure pulse peak is determined by processor 611 in block 604 of Fig. 6. The sampled pressure pulse peak data is digitized by an analog-to-digital (A/D) converter 602 and routed through

block 604 to processor 611, as shown in Fig. 6, where it is stored in memory 612 for later processing.

Figs. 2a and 2b illustrate the position of the pressure sensor 126 within the exhaust manifold of an engine in two alternative embodiments of the present invention. Fig. 2a shows an engine block 210 which houses six cylinders of an internal combustion engine. Exhaust ports 214, 216, and 218 extend outward into exhaust manifold 212. Similarly, exhaust ports 222, 224, and 226 extend into exhaust manifold 220. During the combustion cycle, the exhaust gases are released into exhaust manifolds 212 and 220 and are ultimately routed to port 230 via exhaust paths 221, 223 and 234. Pressure sensor 126 is mounted slightly offset from junction 232 where exhaust paths 221 and 223 connect, as shown in Fig. 2a. At this position, the pressure sensor 126 can accurately detect pressure pulses from each cylinder based on the sequence of cylinder firing. Because the exhaust gas pressure pulses occur at different times, the pressure sensor 126 can detect the peak pressure for each cylinder after firing. After pressure sensor 126 senses a pressure pulse in the exhaust manifold, resulting from the first cylinder firing in a combustion cycle, the sensed data is immediately digitized and stored in the processor memory 612 (described in greater detail below with reference to Figure 6) with the corresponding cylinder number which in this case would be "one." For each subsequent cylinder firing, the operation of the system as described above remains unchanged. The stored pressure data is then used to determine the occurrence of a complete or partial misfiring of a particular cylinder by calculating the running average of the sensed peak pressures for

a complete combustion cycle and a pressure threshold as discussed later with reference to Fig. 6.

Fig. 2b illustrates another alternative embodiment of the present invention in which the pressure sensor is located in a twin-entry turbo exhaust gas system downstream from the exhaust manifold. Extending outward from engine block 210 are a series of exhaust ports 214, 216, 218, and 222, 224, 226 which are connected to exhaust manifolds 212 and 220, respectively, as shown in Fig. 2b. Exhaust manifolds 220 and 221 are connected to exhaust passages 231, 233 which connect to turbocharger 250 at junctions 252 and 254. Pressure sensor 126 is positioned in a passage 256 which connects exhaust passages 231 and 233. The openings 251 and 253 leading into passage 256 from the exhaust passages 231 and 233 are small to prevent the leakage of exhaust gases from one exhaust passage to the other.

The sensor 126 must be offset from the center of passage 256 to reduce the possibility of standing waves being generated therein. These standing waves could alter the pressure readings undesirably. In operation, the exhaust manifold gases are routed downstream toward the turbocharger. As the gases reach junctions 252 and 254, a pressure pulse is created in passage 256 which is sensed by pressure sensor 126. Because the pressure sensor is not positioned in the exhaust manifold as shown in Fig. 1, the sensor must be calibrated accordingly to detect pressure pulses that may have weakened while traveling through exhaust passages 231 and 233. This alternative embodiment of the present invention is desirable because only a single pressure sensor is needed to detect pressure pulses in both exhaust passages 231 and 233.

Fig. 3 illustrates a graph of the typical manifold peak pressure detected by pressure sensor 126 for the engine cylinders when firing properly. Each peak shown in Fig. 3 corresponds to the opening of an exhaust valve of an internal combustion engine and the release of exhaust gases into the exhaust manifold. Once the peak pressures for a specific combustion cycle are sampled and stored in memory 612, processor 611, shown in Fig. 6, determines a running average peak exhaust pressure for all cylinders during a single combustion cycle by adding the pressure peak values and dividing the sum of these values by the number of engine cylinders. For example, if the sum of the pressure peak values for a six cylinder engine is 600 pounds per square inch (PSI), then the average peak pressure for this combustion cycle is 100 PSI. This data is later compared to a pressure threshold to determine the occurrence of a complete or partial misfire. The calculation of the pressure threshold will be addressed in detail with reference to Figs. 6 and 7.

Whenever a complete or partial misfire occurs, the pressure sensor 126 does not detect a pressure pulse or detects a weak pressure pulse from one or more cylinders. As an example, Fig. 4 illustrates a graph of the sampled exhaust manifold pressure with a partial misfiring of cylinder "three." For each combustion cycle, the average peak pressure is determined by processor 611, as shown in Fig. 6, which keeps a running average of the peak exhaust manifold pressure for each cycle. The running average is determined by averaging the previously calculated peak pressures, for all cylinders or several cylinders, with the current sampled peak pressure for a single cylinder firing. If complete or partial misfiring occurs, the average peak exhaust manifold

pressure for the combustion cycle will be lower than when all cylinders are firing properly. Consequently, a possible misfire may be detected by comparing a current sampled peak pressure value (for one cylinder) with the running average peak pressure (for two or more cylinders).

A partial or complete misfire will be declared if the peak pressure for any cylinder is below a minimum pressure value which is calculated by subtracting the pressure threshold from the running average of peak pressures. Fig. 5 illustrates a graph of the average peak pressure and the pressure threshold in relation to the detected peak pressure for each cylinder. The dots at the top of each pressure wave represents the peak pressure sampled by pressure sensor 126. The graph shows that the peak pressure for cylinder "three" is below the minimum pressure value which is the difference between the pressure threshold and the average peak pressure. Thus, in this instance, a misfire would be declared for cylinder "three." The pressure threshold is computed as a function of engine speed and the fuel consumption rate at load and will be discussed in reference to Figs. 6 and 7.

Fig. 6 is a block diagram of the engine misfire detection system in accordance with a preferred embodiment of the present invention. The system comprises a pressure sensor 126, an analog-to-digital converter 602, engine operation sensors 607, and a processor 611 for detecting the peak pressure in block 604 for each cylinder and the average peak pressure 603 sensed over a complete combustion cycle. The processor 611 comprises memory 612 for storing data. The processor 611 further determines a pressure threshold, based on data sensed from engine operation sensors 607, and subtracts the

pressure threshold from the average peak pressure to determine a minimum pressure value. The processor 611 then compares the peak pressure for each cylinder with the minimum pressure value to determine if a misfire has occurred. The engine operation sensors 607 includes an engine speed sensor 608 and coolant temperature sensor 610 which sample each of these engine operation functions. The sampled data is then sent to block 605 to calculate the pressure threshold. Processor 611 is a microprocessor, such as a Motorola 68000 microprocessor, which may be embodied in a vehicle control system already installed on a vehicle, or added as a separate processing feature. Memory 612 may be random access memory (RAM) or any type of programmable memory.

In operation, the pressure sensor 126 samples the peak pressure in the exhaust gas manifold for each cylinder during a combustion cycle. To ensure the accuracy of the peak pressure values, there must be synchronism between the sampling time and the actual time that the pressure within the exhaust manifold has peaked with respect to each cylinder firing. To determine the appropriate sampling time, a sensor is used to monitor the position of the engine cam shaft or crank shaft at a given time. The sampling time of pressure sensor 126 must correspond to each cylinder firing during a combustion cycle. The cam sensor is used to determine which cylinder is firing by sensing the cam gear at top-dead-center (TDC) and subtracting off 60 degrees of revolution, for example, to estimate the firing time for each cylinder.

Once the firing time is determined, the transmission or propagation delay for the exhaust gas pressure waves released from each cylinder upon combustion must be calculated. The transmission delay is measured by calculating the period of time between the firing of the cylinder and the moment at which the peak exhaust gas pressure waves reach pressure sensor 126. This time period varies based on the type of engine, location of the cylinders, pressure sensor position, and other similar factors. Consequently, the transmission delay is a fixed time period that is provided on a chart or table with respect to each engine design. The transmission delay time period is programmed into microprocessor 611 at the pre-production phase of the engine to enable the sensors to sample the peak pressures in the exhaust manifold at the appropriate time to ultimately determine possible engine cylinder misfire.

To ensure the accuracy and integrity of the peak pressure readings, pressure sensor 126 may take multiple samples for each cylinder firing. By taking multiple samples, noise is reduced to improve the accuracy of the sampled peak pressure signal. In this embodiment, pressure sensor 126 samples the peak pressure repeatedly during the time period where the exhaust manifold pressures have peaked. The peak pressure for a particular cylinder firing would be the highest pressure sensed from the multiple samples and is determined in block 604.

An alternative method of determining the peak pressure in block 604 is to create a digital image of the entire manifold pressure waveform for each cylinder firing and then determine the peak pressure signal based on the

highest pressure reading sample over the entire pressure waveform. This method provides an accurate account of the peak pressure signal over the waveform period and would alleviate the need for taking multiple samples and for determining transmission delays as described above.

The sampled pressure data is digitized in an analog-to-digital converter 602 which transforms an analog data signal into a digital data signal. The digitized data signal is then routed through blocks 603 and 604 to processor 611 to calculate both the average peak pressure and the current peak pressure, respectively. In block 603, the sampled exhaust peak pressure values for a complete combustion cycle are averaged and stored in the processor memory 612. Processor 611 develops a running average for each cylinder firing by continuously storing the average peak exhaust pressures in memory 612. Processor 611 compares the average peak exhaust gas pressure generated during a combustion cycle with the current peak exhaust gas pressure of a cylinder to monitor any pressure changes.

The peak pressure for each cylinder is determined in block 604. When pressure sensor 126 monitors the exhaust gas pressure released from a cylinder, it samples the highest pressure detected for each cylinder during a combustion cycle. This peak pressure data is stored in block 604 along with the corresponding cylinder number. The cylinder number for combustion cycle is determined by a cam angle detector which detects a specified cam angle for each rotation of the cam shaft or crank shaft in the engine. For a six cylinder engine, used in the preferred embodiment, the cam gear located on the cam shaft comprises six evenly spaced teeth with a seventh tooth

located between two of the cam gear teeth for detecting the TDC location of the cam gear. Each of the six evenly spaced teeth correspond to one cylinder firing. The seventh tooth is located just before the TDC of the cam gear. Hence the seventh tooth is positioned halfway between the last tooth and TDC to indicated the occurrence of a complete combustion cycle. When the cam angle detector detects the seventh tooth during rotation of the cam gear, it can reset processor 611 to determine the number of each cylinder firing subsequent to the detection of the seventh tooth. Thus, the processor 611 can identify which cylinder has misfired during a combustion cycle, if any. Subsequently, the sampled peak pressure is compared to the minimum pressure value in block 606. If the peak pressure for a cylinder is above the minimum pressure value, no misfire will be declared. If the peak pressure for a cylinder is below the minimum pressure value, a misfire is declared. After detecting a misfire, a user may determine which cylinders have misfired via a conventional audio or visual device attached to the processor output. This information may prove to be important to a technician, for example, when testing an internal combustion engine using the engine cylinder misfire detection system of the present invention.

In the preferred embodiment, a pressure threshold is determined with respect to engine operation for providing a minimum pressure value which must not be exceeded by the peak pressure for a monitored cylinder in order for the system to declare a complete or partial misfire. The pressure threshold represents a percentage or an absolute pressure which is subtracted from the running average peak pressure at the end of a complete combustion cycle to

determine the minimum pressure value which may vary for each combustion cycle. Sensors 607 are placed in or on the engine to sample data for calculating a pressure threshold based on various engine parameters. Existing engine sensors may be used, however, to detect these engine operation parameters.

In calculating the pressure threshold, certain engine operating parameters should take precedence over other parameters. For example, the most important engine operation parameter that is used to calculate a pressure threshold is the fuel consumption rate. In essence, by monitoring the amount of fuel that is used in each cylinder during a combustion cycle, the user can accurately detect abnormalities in fuel consumption. Variations in fuel consumption may be reflected in the pressure threshold to indicate whether an engine cylinder misfire has occurred. The second most important engine operation parameter would be the engine speed. Based on the speed of the engine, specifically the rotation of the cam shaft, a user could also detect whether there are abnormalities in engine cylinder firing. A decrease in the engine speed, for example, may indicate that an engine cylinder has misfired. Thus, this information is important in calculating an accurate pressure threshold to detect the misfire of an engine cylinder. The coolant temperature is used to determine whether to test for engine cylinder misfires. When the engine is cold, as determined by the coolant temperature, processor 611 does not test for engine cylinder misfires. Nevertheless, when the coolant temperature has reached a predetermined temperature, a signal is sent to the microprocessor 611 to test for engine cylinder misfires.

The fuel consumption rate is determined and stored in memory at the pre-production stage. This measurement is used to determine the actual fuel consumption rate in a spark-ignited natural gas engine as a percentage of the fuel rate at 100 percent load. The actual fuel consumption rate is determined using a gas mass flow sensor and/or other sensors which indicate the amount of fuel entering the engine and determine the air/fuel ratio. The gas mass flow sensor monitors the volume of gas or fuel flowing into the engine cylinders. An exhaust gas oxygen sensor may also be used in the present invention to monitor the residual oxygen escaping from the engine to provide feedback on the amount of fuel which has combusted. Intake air pressure and intake air temperature sensors may be used to determine the mass of air that enters the engine cylinders to ultimately determine the air/fuel ratio. The fuel consumption rate data is stored in the processor memory 612 and used to calculate a pressure threshold. If fuel consumption in the engine increases, the pressure threshold would also increase due to the increased pressure developed in the exhaust as a result of the excess fuel combustion.

An alternative method of determining the air/fuel ratio is to monitor the average peak exhaust manifold pressure during a combustion cycle. The average peak exhaust manifold pressure increases as the fuel entering the engine is leaned out. Thus, the increase in the average peak exhaust manifold pressure provides an indication of the air/fuel mixture entering the engine at a given time. Because the air/fuel ratio provides an indication of the amount of fuel consumed during a combustion cycle, this ratio is used in determining the fuel consumption rate at engine load.

The engine speed is sampled by positioning a sensor to monitor the rotation of the cam shaft. Engine speed is determined by sampling the speed between each tooth of the cam gear as the cam shaft rotates. Hence, when all six teeth have completed one rotation, the sensor has sampled engine speed data for each cylinder for a complete combustion cycle. The sampled data is stored in the processor memory 612 and used to calculate the pressure threshold. As the engine speed increases, a higher threshold value is required to compensate for the increased exhaust pressure resulting from the increased engine speed. This result occurs due to the increase in average peak pressure with respect to speed and load which increases the pressure threshold as the speed increases.

The coolant temperature sensor 610 monitors the temperature of the coolant as it travels out of the engine to the radiator. Thus, the sensor is positioned in the fluid line which connects the engine to the radiator. As stated above, this sensor determines when to begin testing for engine cylinder misfires. Once the coolant temperature reaches a predetermined level, the microprocessor 611 begins to test for engine cylinder misfires by sampling the average peak exhaust manifold gas pressures. If the sampled data reflects a high coolant temperature, the pressure threshold value will be increased to compensate for the variability of the engine coolant temperature.

The engine speed and fuel consumption rate data are provided to block 605 to calculate a pressure threshold level. The stored engine sensor data is used to calculate the pressure threshold by indexing the sensed information into a three-dimensional table or data register stored in block 605. The three

dimensional data register includes a predetermined pressure threshold values that vary based on the calculated engine speed and fuel consumption rate data.

A predetermined pressure threshold value is calculated while running the engine in a testing cell. By conducting tests at different pressures and fuel rates, a pressure threshold value can be determined for specific engine operating parameters. This threshold value is based on the desired minimum pressure value which represents the lowest pressure level at which the engine operates efficiently as determined by the user. As discussed above, in a spark-ignited natural gas engine, the fuel is leaned out until a misfire occurs and then fuel is added to the air/fuel mixture to a point just above misfire to allow the engine to operate efficiently. This is represented in the present invention as the minimum pressure value. The pressure threshold may be represented as a percentage or an absolute pressure. In essence, the pressure threshold is the difference between the average peak pressure and the minimum pressure value. As the engine operating parameters change, so does the pressure threshold to compensate for the engine operating variations and still maintain a desired minimum pressure value. The pressure threshold percentage should be between 15 to 30 percent based on the engine operation parameters. For example, if the engine speed is 2500 rpm and the fuel rate is 5 milliliters per second during a combustion cycle, a pressure threshold percentage may be determined during testing to represent the variation in pressure required to compensate for the sensed engine conditions. If the average peak pressure is 50 PSI and the calculated pressure threshold is 30 percent, the minimum pressure value would be 35 PSI. As an absolute

pressure, the pressure threshold in this example would be 15 PSI. If the sensed engine speed increases, however, a higher pressure threshold may be needed to account for the variation in pressure as a result of the engine speed increase. One skilled in the art should appreciate that the pressure threshold may be calculated using only one or two of the engine operation parameters. The pressure threshold is calculated in block 605 and sent to block 606 to determine the minimum pressure value.

An engine cylinder misfire is declared when the exhaust manifold pressure sensed after a cylinder firing is below a minimum pressure value which is calculated and compared to the peak exhaust pressure for each cylinder in block 606. The minimum pressure value represents the lowest pressure level at which the engine can efficiently operate based on the exhaust pressure and engine operation parameters sensed during a combustion cycle. For example, if the average peak exhaust pressure is 50 PSI and the pressure threshold is 10 percent, then the minimum pressure value is 45 PSI. Any sensed peak exhaust manifold pressure below 45 PSI would be declared a misfire because at 45 PSI and above sufficient cylinder combustion exists for the engine to operate efficiently. A user of the present invention may determine the level of efficiency at which they desire an engine to run. This level of efficiency may be varied based on the calculated pressure threshold. When the exhaust pressure for a cylinder drops below the level of efficiency, a misfire is declared and recorded in the processor memory 612.

Fig. 7 is a flowchart of a process implemented by software in processor 611 used to determine the occurrence of a misfire based on the calculated

average peak pressure and pressure threshold. In block 701, the coolant temperature is sensed to determine whether to activate processor 611 to detect engine cylinder misfires. If the coolant temperature is above a predetermined level such as 50 degrees fahrenheit, processor 611 will activate the engine cylinder misfire detection process, as shown in step 702. If not, then the coolant temperature will continue to be monitored to determine if the temperature meets or exceeds the predetermined level. In block 703, data sampled by pressure sensor 126 is read into processor 611, both shown in Fig. 6. The peak pressure for each cylinder firing is determined in block 704 and the data is stored in processor memory 612. The processor then computes a new running average of peak pressures based in the current peak pressure (for one cylinder firing) and the previously calculated average peak pressure (for six cylinder firings) in block 705. In block 706, processor 611 reads the fuel consumption rate data from memory 612. The data sampled from the engine speed sensor is then read by processor 611 in block 707. The pressure threshold is calculated in block 708 based on the data read in steps 706 and 707. The pressure threshold is subtracted from the average peak pressure in block 709 to yield a minimum pressure value. If the sensed peak pressure for any cylinder is below the minimum pressure value, determined in block 710, then the processor 611 determines the number of the cylinder which has misfired in block 711. The engine cylinder misfire data is then presented to the operator or stored for later retrieval in block 713. If the current peak pressure is not below the minimum pressure value, no misfire is detected, as

shown in block 713, and the processor proceeds to read data from the coolant temperature sensor, in block 701, for another combustion event.

Once an engine cylinder misfire has been detected, an operator could use the data stored in processor 611 memory to optimize the performance of an internal combustion engine by adjusting various engine parameters. The data may also be used as an input to other engine control algorithms to enhance engine operation functions. For example, engine misfire detection data may be used to optimize the air/fuel ratio, spark timing, spark energy, multiple sparks, wastegate control, variable geometry turbo control and other related engine functions.

Fig. 8 illustrates a process of obtaining optimal fuel efficiency using the system and method of determining engine cylinder misfire of the present invention. In the preferred natural gas environment, the spark-ignited engine will operate at a steady state speed while the fuel is slowly leaned out until an engine misfire occurs, as shown in block 801. Engine cylinder misfire is then detected using the engine cylinder misfire detection system of the preferred embodiment, as shown in block 802. After the misfire occurs, the fuel is then minimally increased to a level near the misfiring point to enable the engine to run as lean as possible, as shown in block 803. Operating the natural gas engine near the misfire point greatly improves fuel efficiency and economy.

The system described herein detects engine misfires continuously when a vehicle is in operation. By detecting misfires efficiently and accurately as described above, the present invention provides a system and method to reduce engine wear using a cost effective approach.

While the invention has been described with reference to the aforementioned embodiments, it should be appreciated by those skilled in the art that the invention may be practiced otherwise than as specifically described herein without departing from the spirit and scope of the invention. It is therefore understood that the spirit and scope of the invention be limited only by the appended claims.

INDUSTRIAL APPLICABILITY

The system and method for detecting engine cylinder misfire in internal combustion engines would be useful in any environment where a user desires to constantly monitor the average peak exhaust gas pressure during a combustion cycle and the operational characteristics of an engine to determine when engine operation is abnormal or outside of prescribed tolerances, such as with stationary power sources and vehicle engines.

CLAIMS:

1. A system for detecting an engine cylinder misfire in an internal combustion engine comprising:

pressure sensing means mounted in an exhaust path of the internal combustion engine for sensing the pressure of the exhaust gas flowing through said exhaust path;

engine operation detecting means for detecting operating characteristics of the internal combustion engine, said operating characteristics including at least one of the rotational speed, fuel consumption rate and coolant temperature of the internal combustion engine; and

data processing means connected with said engine operation detecting means and said pressure sensing means for receiving the sensed pressure from said pressure sensing means for calculating a minimum pressure value corresponding to said operating characteristics and for comparing said sensed pressure with said minimum pressure value to determine if an engine cylinder misfire has occurred.

2. A system according to claim 1 wherein said engine operation detecting means includes a sensing means for monitoring and sensing said operating characteristics in real-time.

3. A system according to claim 1 wherein said data processing means includes a memory means for storing data sensed from said pressure sensing means and said engine operating detecting means.

4. A system according to claim 1 wherein said data processing means includes an average exhaust pressure calculating means for calculating the average exhaust pressure sensed by said pressure sensing means for each cylinder of said internal combustion engine during a complete combustion cycle.

5. A system according to claim 4 wherein said data processing means includes a minimum pressure value calculating means for calculating a minimum pressure value by first calculating a pressure threshold using said detected operating characteristics of the internal combustion engine and subtracting said pressure threshold from said average exhaust pressure to yield said minimum pressure value.

6. A system according to claim 4 wherein said data processing means includes a running average calculating means which averages an average exhaust pressure value determined by said average exhaust pressure calculating means and a current exhaust pressure value to yield a running average exhaust pressure value, said running average exhaust pressure value replacing said average exhaust pressure value after each cylinder firing.

7. A system according to claim 1 wherein said pressure sensing means includes a peak pressure sensing means for sensing the highest pressure released from each cylinder of said internal combustion engine during each combustion cycle.

8. A system according to claim 1 further comprising analog-to-digital converter means connected with said pressure sensing means and said data processing means for receiving an analog electrical signal representative of the pressure in said exhaust path from said pressure sensing means, for converting said analog electrical signal to a digital signal, and for providing said digital signal to said data processing means.

9. A system according to claim 8 further comprising a peak detection means connected with said analog-to-digital converter means for receiving said digital signal and for determining the maximum sensed pressure based on said digital signal for each cylinder of the internal combustion engine during a normal combustion cycle.

10. A system according to claim 1 wherein said pressure sensing means is a gauge-type pressure sensor.

11. A system according to claim 10 wherein said gauge-type pressure sensor is a piezoelectric sensor.

12. A system according to claim 10 wherein said gauge-type pressure sensor is a capacitive ceramic sensor.

13. A system according to claim 1 wherein said pressure sensing means includes a single pressure sensor.

14. A system according to claim 1 wherein said data processing means includes a cylinder number detecting means for detecting which cylinder has fired or misfired during a combustion cycle.

15. A method of detecting an engine cylinder misfire in an internal combustion engine comprising the steps of:

detecting the exhaust gas pressure generated by the internal combustion engine;

detecting operating characteristics of the internal combustion engine, said operating characteristics including at least one of the rotational speed, fuel consumption rate and coolant temperature of the internal combustion engine;

calculating a minimum pressure value corresponding to said operating characteristics;

comparing said minimum pressure value to the exhaust gas pressure; and

generating a signal indicating if said exhaust gas pressure is less than said minimum pressure value to declare the occurrence of an engine cylinder misfire.

16. A method according to claim 15 wherein said step of calculating the minimum pressure value includes the step of calculating an average exhaust

pressure for a complete combustion cycle and the step of calculating a minimum pressure value using said detected operating characteristics of the internal combustion engine, said step of calculating the said minimum pressure valve includes the step of calculating a pressure threshold using said detected operating characteristics of the internal combustion engine and subtracting the pressure threshold from said average exhaust gas pressure to yield said minimum pressure value.

17. A method according to claim 15 further comprising the step of detecting an engine cylinder number for determining which cylinder has fired or misfired during a combustion cycle.

18. A method according to claim 15 further comprising the step of detecting an air/fuel ratio for determining the air to fuel mixture entering each cylinder during a combustion cycle.

19. A method of detecting an engine cylinder misfire in an internal combustion engine to determine an optimal level of engine operation comprising the steps of:

decreasing the amount of fuel supplied to one or more cylinders of an internal combustion engine to cause an engine cylinder misfire;

detecting said engine cylinder misfire in said internal combustion engine caused by an insufficient supply of said fuel; and

increasing said amount of fuel supplied to said one or more cylinders in response to said detected misfire to a level sufficient to enable said internal combustion engine to operate without the occurrence of engine cylinder misfires at an optimal fuel efficiency.

20. A system for detecting an engine cylinder misfire in an internal combustion engine comprising:

a pressure sensor mounted in an exhaust path of the internal combustion engine;

engine operation sensors positioned on or within the internal combustion engine for detecting the operating characteristics of the internal combustion engine, said operating characteristics including at least one of the rotational speed, fuel consumption rate and coolant temperature of the internal combustion engine; and

a processor connected with said engine operation sensors and said pressure sensor for calculating a minimum pressure value to determine if an engine misfire has occurred, said processor comprising a comparison means for comparing the exhaust pressure sensed by said pressure sensor to said minimum pressure value to determine if an engine cylinder misfire has occurred.

21. A system according to claim 20 wherein said pressure sensor is positioned in a passage which connects at least two of said exhaust paths of said internal combustion engine.

22. A system according to claim 21 wherein said passage includes inlets at the ends of said passage, said inlets being smaller in diameter than the center area of said passage to restrict leakage of exhaust gases between said exhaust paths.

23. A system according to claim 21 wherein said pressure sensor is offset from the center of said passage to prevent standing waves which may be generated within said passage.

24. A system according to claim 20 further comprising an analog-to-digital converter connected with said pressure sensor and said processor for receiving an analog electrical signal representative of the pressure in said exhaust path from said pressure sensor, for converting said analog electrical signal to a digital signal, and for providing said digital signal to said processor.

25. A system according to claim 20 wherein said pressure sensor is a gauge-type pressure sensor.

26. A system according to claim 25 wherein said gauge-type pressure sensor is a piezoelectric sensor.

27. A system according to claim 25 wherein said gauge-type pressure sensor is a capacitive ceramic sensor.

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1N Part A files AAJCR, AHQ

Int Cl (Ed.6): F02B 77/08F, 77/08F1 and G01M 15/00D4E4, 15/00D6

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	WO95/02174A1	Kavlico Corpn. - whole document but see esp. pp.14-17 and original claim 10	1-4 at least
A	US5369989	assigned to Ford Motor Co. - see esp. cols.5-7 and Figs.2, 9-12	1-4, 21 at least
X	US5287283	assigned to Mitsubishi Denki - see esp. cols.8,9 and Figs.7-9	1-6, 8, 13-17, 20.21,24 at least
A	US3924457	assigned to K K Toyota - see esp. Fig.7, cols.14-17 and claim 10	1-4 at least

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